Optical Design of the WFIRST-AFTA Wide-Field Instrument

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Abstract: The WFIRST-AFTA Wide-Field Infrared Survey Telescope TMA optical design provides 0.28-sq° FOV Wide Field Channel at 0.11" pixel scale, operating at wavelengths between 0.76-2.0µm, including a spectrograph mode (1.35-1.95µm.) An Integral Field Channel provides a discrete 3"x3.15" field at 0.15" sampling.

OCIS codes: (110.0110) Imaging systems; (110.6770) Telescopes; (120.6085) Space instrumentation; (350.1260) Astronomical optics; (350.6090) Space optics

1. Introduction

The optical design of the Wide-Field InfraRed Survey Telescope (WFIRST)[1] Wide-Field Channel (WFC) provides ~1/3-square degree of field coverage (0.28 square degree instantaneous) at 0.11 arcsecond pixel scale. This is accomplished using a 2.36-meter diameter (Hubble-Class) aperture Three Mirror Anastigmat (TMA) optical design that was constrained and influenced by a combination of existing hardware, design heritage, science interests and volume constraints. The result is a design with a focal plane of 300 million pixels capable of diffraction-limited imaging, operating in six panchromatic bands between 0.6 – 2.0µm, or multi-spectral imaging mode from 1.35-1.95µm. Within the instrument enclosure is a separate Integral Field Channel (IFC) providing discrete spectral analysis over a 3"x3" field at 0.15" spatial and R=100 average spectral resolution.

2. Optical Design Layout Overview

This incarnation of WFIRST's optical design is designated *AFTA* (Astrophysics Focused Telescope Assets) and uses existing telescope components, repurposed to NASA for scientific use. This paper discusses the "Cycle 4" design, a snapshot of an evolving design as trade studies and analyses are completed.

The WFIRST-AFTA TMA optical design is anchored to the repurposed assets' size and figures. While the Primary Mirror (T1) shape is fixed, minor changes in the curvature, conic and position of the Secondary Mirror (T2) are easily implemented. An Entrance Aperture Plate (EAP) at the intermediate focus passes the WFC's field into the instrument enclosure. A powered mirror within the instrument (M3) then works in concert with T1 & T2 to produce a corrected field across the 6x3 array of sensors in the Focal Plane Array (FPA) while forming a pupil to allow for a cold stop and filter elements. Two fold mirrors are used for packaging. The layout is shown in Figure 1.

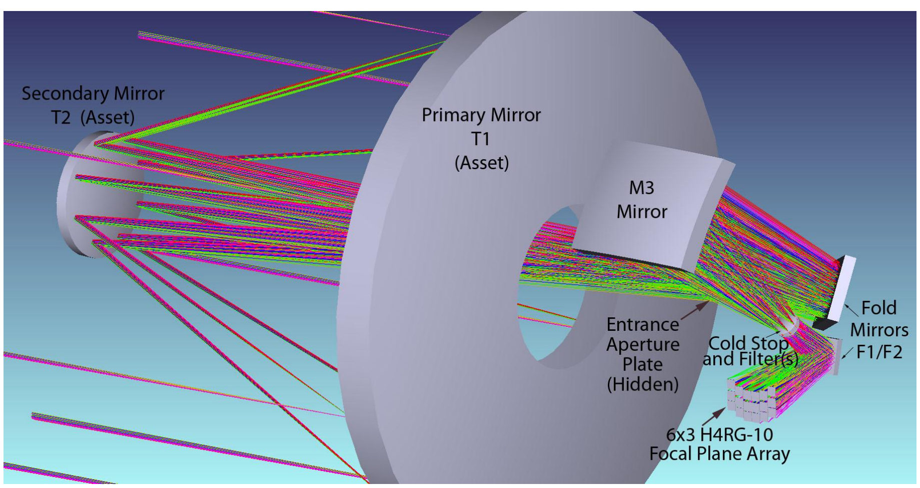

Figure 1. Optical Layout of WFIRST AFTA Wide-Field Instrument (Design Cycle 4)

The basic optical design is decidedly simple for fabrication, integration and test purposes. This approach begins with the base optical design; all three powered mirrors are optically co-axial and simple conics. We considered more complicated designs, including the use of tilted and de-centered mirrors and Zernike and/or anamorphic surface figures.[2,3] TMA designs are widely preferred for high A*Omega telescopes such as JWST and ATLAST.

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The primary mirror, referred to here as Telescope mirror 1 (T1), is a fast f/1.2 primary with a linear central obscuration of 31%. It is a light-weighted mirror using a hollow honeycomb core. T1 and Telescope mirror 2 (T2) together form an ~f/8, intermediate focus. This focus is uncorrected, with a large caustic image and strongly curved image surface. You will note the off-axis field bias (seen in Figure 1); this is typical in all TMA systems.

Within the instrument, Mirror 3 (M3) is almost a 1:1 magnification relay of the intermediate image to the focal plane. Working in concert with T1 & T2, these 3 powered mirrors form the large corrected field of the TMA.

A pupil is formed between M3 and the focal plane. With a diameter of approximately 100mm, the pupil allows for the insertion of bandpass filters and spectral dispersion elements via an element wheel. Finally, in order to package the system into the volume constraints, two fold mirrors were used.

3. Why is WFIRST-AFTA significant?

Before walking through the finer details of the optics, it is important to understand the big picture of both the science motivations and how the observatory is designed to meet these goals.

Dark energy mission concepts have been in development since the 1998 discovery of the increasing rate of expansion rate of the universe.[4,5] The WFIRST-AFTA dark energy program probes the expansion history of the Universe and the growth of cosmic structure with multiple methods in overlapping redshift ranges. While previous dark energy mission concepts performed one or two science surveys, WFIRST-AFTA delivers multiple surveys with 2-4 times the scientific strength of previous concepts. The increased étendue (A*Omega) allows for faster, wider surveys, as well as better calibration. Specifically, WFIRST-AFTA aims to tightly constrain the properties of dark energy, the consistency of General Relativity, and the curvature of space. The High Latitude Survey is designed with sub-percent control of systematics.

WFIRST-AFTA actively seeks to leverage mature technology for flight readiness and cost control. There is a great “bang for the buck” value proposition in the mission. WFIRST potentially enhances other space missions and ground-based observatories. For example, WFIRST would enhance Euclid with higher resolution and galaxy shape, IFU spectra and extended redshift range. Also, while WFIRST surveys wide and discovers high-z galaxies, stellar explosions and exoplanets, the James Webb performs more detailed spectroscopy, analysis of properties and detail of structure. WFIRST would serve well as JWST target finder. The amount of data WFIRST-AFTA is capable of generating opens up the knowledge of the universe to everyone, from students to Nobel prize-seeking scientists.

4. Observatory Integration

The WFIRST-AFTA observatory is being designed around existing hardware to accomplish these objectives. In Figure 2, the donated hardware is shown in black; these structures are already built and awaiting integration into the observatory.

What you notice first is the Outer Barrel Assembly. The OBA is less than 1/3 the length of Hubble’s sunshade, as the primary mirror is half the f/# and the baffle does not extend far in front of the secondary mount. In fact, the whole observatory is half HST’s length. The red area is the outer surface radiator for the Wide Field Instrument.

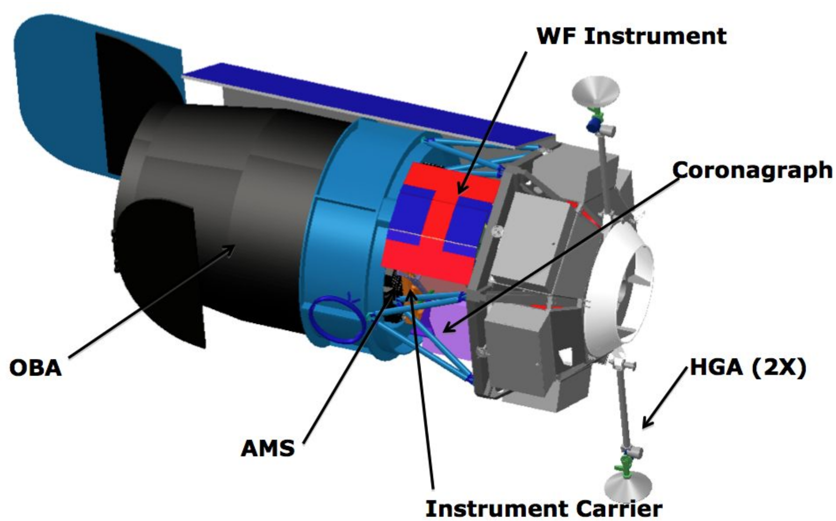

Figure 2. WFIRST Observatory Layout

Removing the OBA reveals the full extent of the reuse hardware, still shown in black. (Figure 3) The optical design is anchored to the donated assets' size and figures. The reuse hardware includes:

- The telescope mirrors T1 & T2,
- Secondary support struts (with actuators) and forward metering structure,
- Aft Metering Structure (AMS), the main support structure and
- The Outer Barrel Assembly (OBA) and actuated doors.

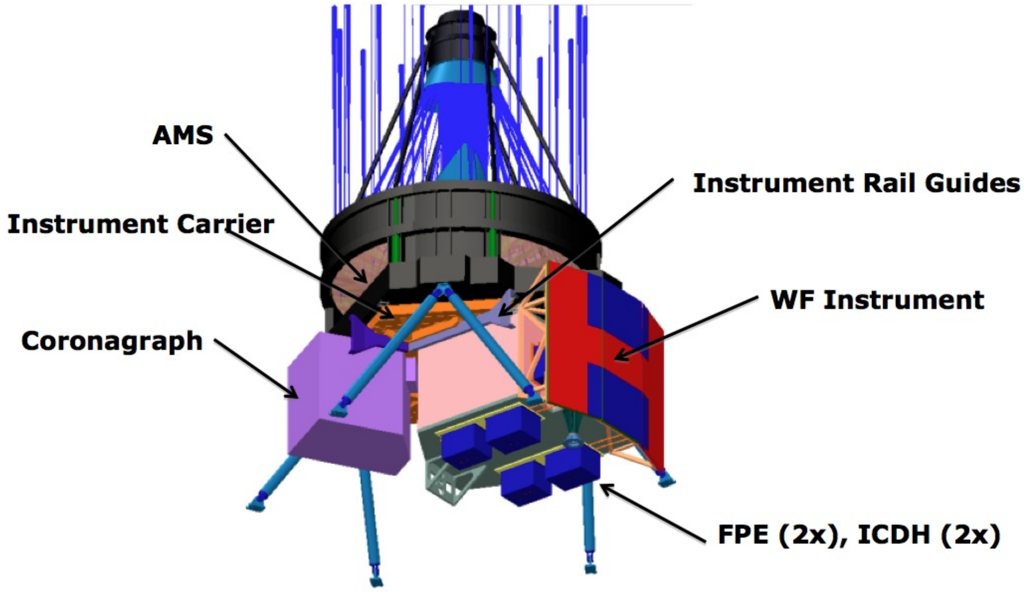

Figure 3. WFIRST Instrument Carrier with Wide Field Instrument and Coronagraph Instrument. (Design Cycle 4)

Note that the secondary sunshade and inner baffle (light blue) are new. They have been sculpted to precisely match our fields, and play an important role in stray light control. While the form of the Primary Mirror (T1) is more fixed, we had freedom to allow minor changes in the curvature and position of the Secondary Mirror (T2) for repolishing.

You also see how the instruments integrate to the telescope. There are two proposed instruments: the Coronagraph Instrument (CI, in purple) and the Wide Field Instrument (WFI, in pink.) The WFI contains both the Wide Field Channel (WFC) & Integral Field Channel (IFC) inside. Note that under the main Aft Metering Structure (AMS) is the orange Instrument Carrier. The IC supports the load of the instrument suite, with a rail system that allows the CI & WFI to be removed in a manner analogous to HST instruments. There is a notable difference in Hubble's instruments; the WFI is about 4 times the volume as the Hubble Wide Field Camera 3! (See Figure 4.)

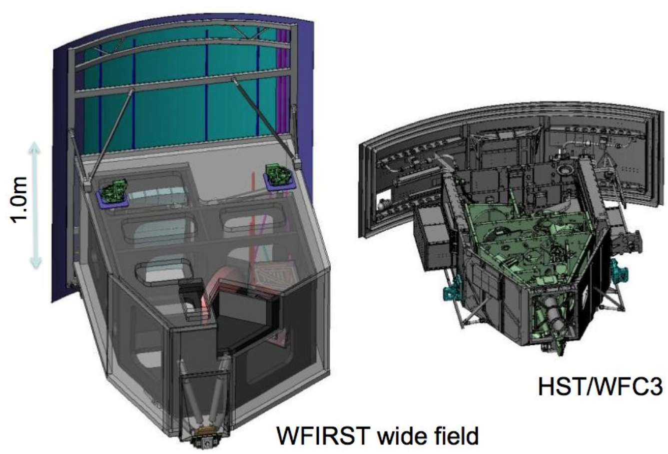

Figure 4. Wide field Instrument Shares Architecture & Heritage with HST/WFC3

5. WFIRST Wide Field Channel FOV and Optical Layout – Cycle 4

To understand the need for the volume, you must understand how the field of view (FOV) plays into the design. Figure 5 shows the comparative fields of other space telescope instruments: The Hubble WFC3 ~2'x2' field sits on HST's optical axis, the ACS is 6' off-axis with a slightly larger field, and JWST's NIRCam is 2.2'x4.4', located 8' off-axis. Each of these fields are much smaller than our view of the moon as seen from earth. For comparison, WFIRST's Wide Field Channel's FOV spans almost two moons, with over 1,000 instantaneous square arcminutes. The WFC A*Omega is ~220x the WFC/IR, ~140x the WFC/VIS, ~90x the ACS, and ~13x NIRCam.

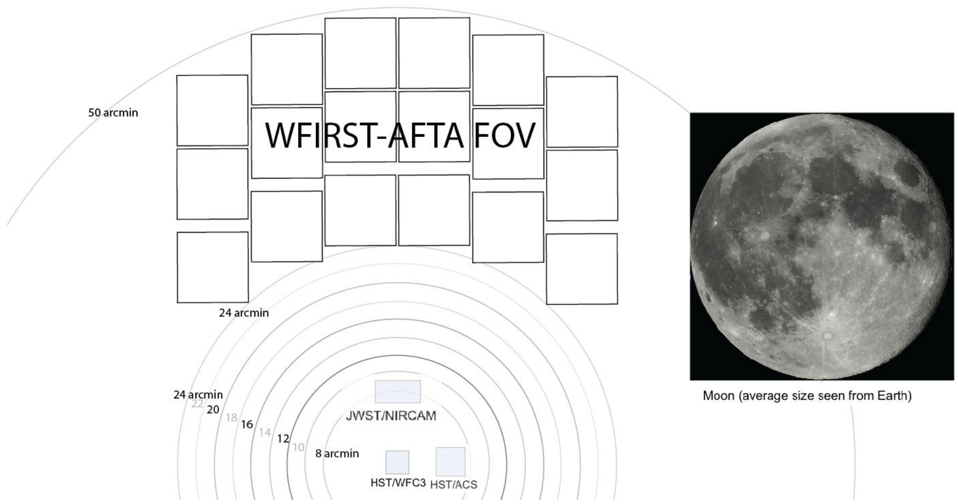

Figure 5. Comparative Field of Views of Space Telescope Cameras

The WFI uses a 6 x 3 array of sensors, arranged to follow the natural annular curve (between 24' and 50' off-axis) of our TMA optimized field. The WFC's 18 H4RG HgCdTe sensors each span 7.5'x7.5', and at 16.7 million pixels each, create a 300 megapixel focal plane! This isn't just a light bucket; The WFC maintains diffraction-limited performance with a 0.11" pixel pitch.

To illustrate this point: Between 2008-2012, the Panchromatic Hubble Andromeda Treasury (PHAT) was completed... using 414 pointings of the HST/ACS & WFC. WFIRST-AFTA could repeat that coverage in just two Wide Field Channel pointings (or four, including overlapping observations; again a 100x increase in efficiency.)

When we slide the WFI bench out of the observatory and pop the hood, we see how the optics path and opto-mechanic components are shoehorned into the optics bench. Remove the thermal enclosure and bench (Figure 6) …

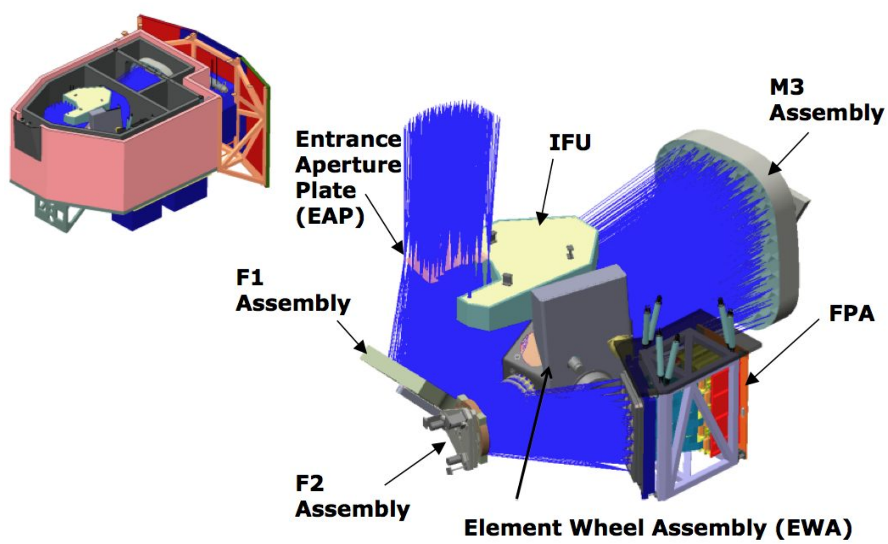

Figure 6. The Internal Opto-Mechanical Layout of the WFI

…and now we can see the full optical workings. The Entrance Aperture Plate (EAP) at the telescope intermediate focus position passes only the WF Channel's field into the instrument enclosure. Notice how the IFU "shoebox" fits into the space above the WFC optical path. Also, the IFU only captures a separate, almost singular field. Also revealed are the element wheel and Focal Plane Array (FPA) structures, and the F2 focus mechanism.

Continuing the peel-back of the structure, let's look purely at the ray trace. (Figure 7.)

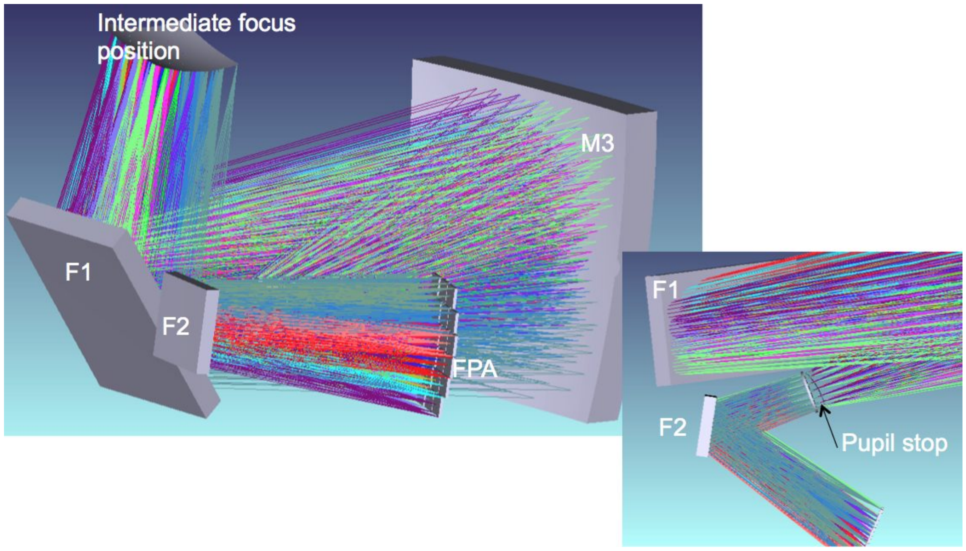

Figure 7. WFI Ray Trace Views

After passing through the Entrance Aperture Plate, the ray bundles from the telescope intermediate focus are folded to the powered Mirror 3 (M3), which relays the corrected wide-field image to the FPA. For scale, M3 is 80 cm corner-to-corner. It and the other mirrors are mounted on zero-stress flexures. Once light passes the pupil, it reflects off F2 to the focal plane array. The last fold mirror (F2) has 5 degrees of freedom to provide on-orbit focus for the Wide Field Channel. Optical alignment will employ various metrology and phase retrieval techniques.[6] These will be discussed in future proceedings.

6. Select Opto-Mechanical Components

6.1. Wide-Field Element Wheel

M3 also forms an accessible pupil where we can place our element wheel. This represents about a 25:1 reduction of the telescope aperture, which results in an angular range of ±15° passing through the pupil.

Figure 8 shows the layout of the filter wheel. Here we see how the grism, six bandpass filters plus a null for counter-balance and calibration all fit into our filter wheel. The optical layouts for the element wheel modes are shown in Figures 9 & 10.

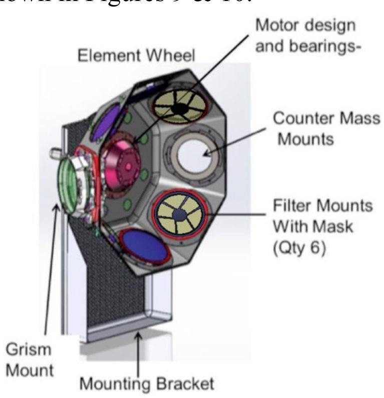

Figure 8. The WFI Element Wheel

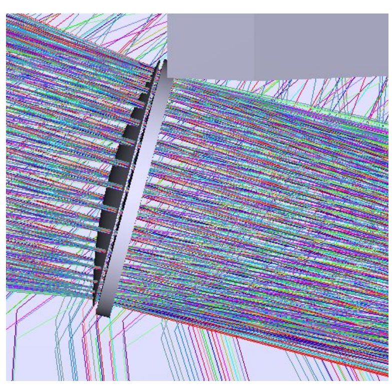

Figure 9. Wide-Field Imaging Mode Bandpass Filter (6 positions)

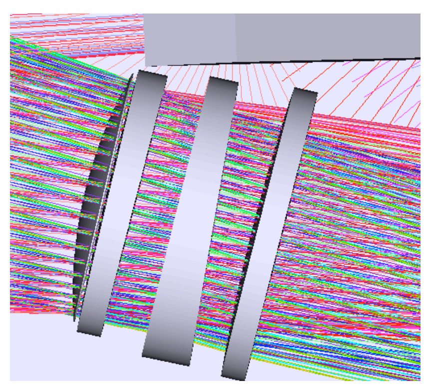

Figure 10. Wide-Field Spectrograph Mode 3-Element Grism (1 position)

In imaging mode, each bandpass filter, operating in six panchromatic bands between 0.76 – 2.0µm, are placed just behind the pupil mask. In spectrographic mode (1.35 – 1.95µm), three elements form the wavelength dispersing grism, designed by Qian Gong. All elements are fused silica with spherical or plano figures. Binary and Phase diffraction surfaces provide both almost uniform dispersion and wavefront correction across the entire field. Compared to the bandpass filter images, the spectral image is held par-focal and with zero deviation at the central wavelength.

6.2. Lyot Stop (Cold Mask)

At the pupil, the Lyot stop blocks the scatter and emissions from the telescope struts and baffles. The pupil mask is integrated into the filter mount, and is curved to match the best focus of the telescope central obscuration, the secondary support struts, and the primary aperture. Each mask has a custom cutout, apropos for the waveband's SNR, based on the needed thermal and stray light control.

Our baseline design has the telescope below room temperature, and the instrument bench and pupil at 170°K. The mask was designed to provide a full thermal block of all telescope structures. (Figure 11) To completely eliminate these sources for all fields, there is an average of 8% transmission loss. Initial analysis indicates that only the longer-wave channels will need the full cold stop; other channels may just need a thinner structure or simply the outer diameter.

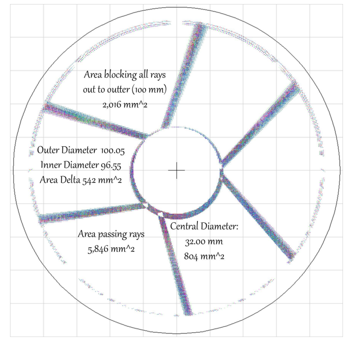

Figure 11. (Right) The WFC Pupil Cold Stop Mask Geometry.

6.3. Focal Plane Array

The Focal Plane Array consists of 18 individual H4RG-10 detectors, each with 4,088 x 4,088 10µm active pixels. The sensors are laid out in a 6 columns of 3 sensors each, in a pattern matching the off-axis TMA field annulus. Each sensor is custom shimmed in the array with a tilt and piston to match a field curvature of about 16 meters, allowing a modest performance gain over a perfectly flat field. A 90°K cold plate surrounds the array to prevent heat leakage and as a final stray light component.

7. Imager Performance

In our optical design, we maintained a maximum root mean square (RMS) polychromatic wavefront error of 45nm across the entire field. This is half of the diffraction-limited 90nm budget (based on 1/13th wave at 1.2µm.) The optical design residual imaging performance of each sensor of the Wide Field Channel is shown in Figure 12. (Note the left-right symmetry.) The geometric spot diagrams for the center of each sensor show they are well within the Airy Disk diameter, also shown below.

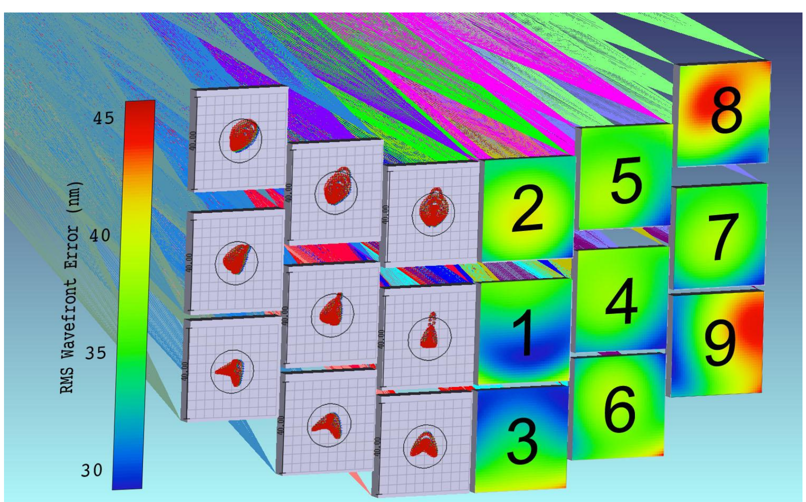

Figure 12. Optical Design Residual Performance of the Wide-Field Imager: Polychromatic spot diagram (18µm diameter Airy Disc circle shown) and WFE (in nm) across each sensor (1-9 of 18).

The distortion of the wide-field is a simple function of radial field angle. This is a feature of all TMA optical designs; distortion is not corrected. However, the platescale is maintained to ±1%. (Figure 13.a/b) Calibration of the as-built field map will occur during integration & testing, and will be further characterized on-orbit.

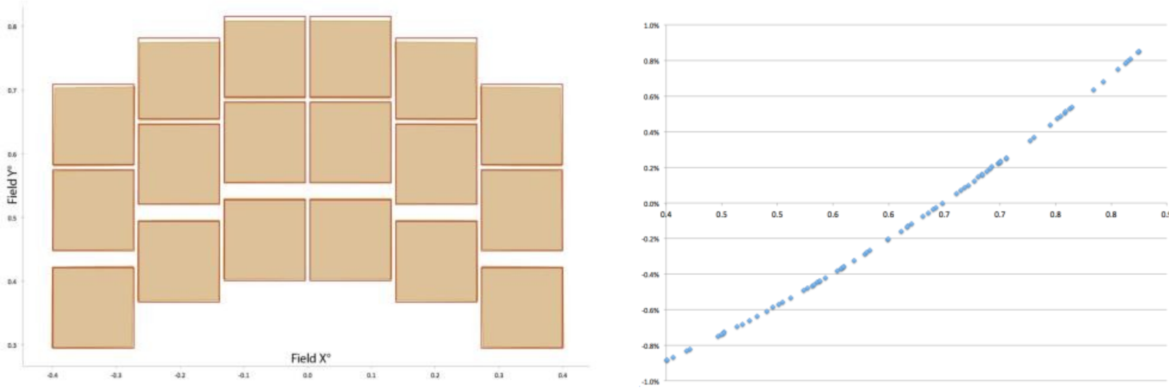

Figure 13.a. Optical distortion; Square outline: Zero distortion. Filled trapezoids: Actual fields. b.Platescale as a function of field

8. Integral Field Unit

A separate channel within the Wide-Field instrument enclosure is the Integral Field Channel (IFC.) The purpose of such a unit is to perform spectroscopy on a discrete sky sample, without contamination from adjacent fields. A very small 3” x 3.15” field is relayed to an f/291 image. The field is sliced and re-arranged into a continuous slit. This slit is then relayed through a spectrograph (R~100), allowing for the multiplexing spectral analysis of each individual 0.15” x 0.15” field. The layout is shown in Figure 14.

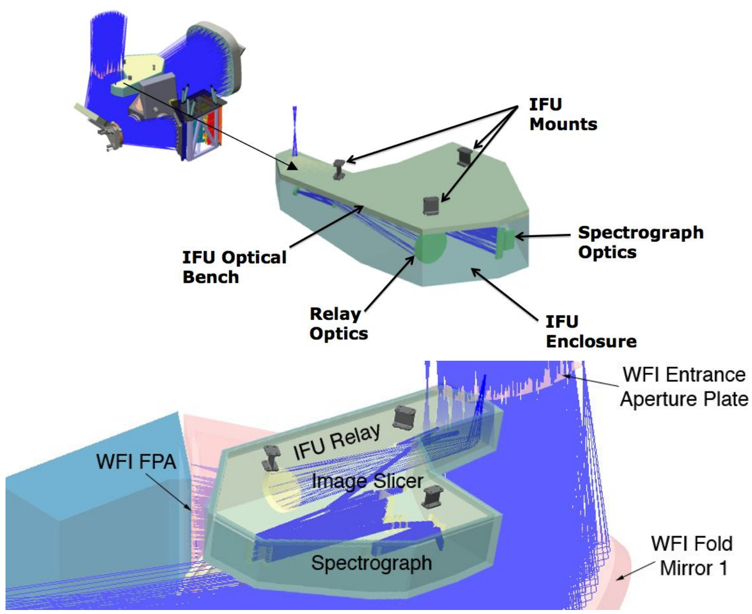

Figure 14. Integral Field Unit, located within the WFI enclosure.

The image slicer is a multi-step process; First, 21 10mm x 0.5mm slicer mirrors form individual pupils. Then, 21 pupil mirrors reimage slices to single 50mm output slit. And finally, 21 output field mirrors create the single “pseudo-slit” slicer output. (That’s 63 mirrors total!) This system was designed by David Vaughnn, based on “current art” for this image slicing method.

The Spectrograph uses a tri-prism (R~100) for dispersion, which is integrated with the collimation and focus mirrors to reduce the pseudo-slit to 18mm. This allows 2 pixels per 0.15” sample. We are baselining a flight spare H2RG for the sensor. The final images are near diffraction-limited at the shortest wavelength.

9. Stray Light Mitigation

As mentioned before, the custom telescope baffles play an important role in the stray light control. A reverse ray trace quickly shows the benefit of a sculpted baffle in reducing or nulling rogue rays to the intermediate focus. (See Figure 15.) Internal apertures, prior to the internal pupil, eliminate all remaining rogue rays.

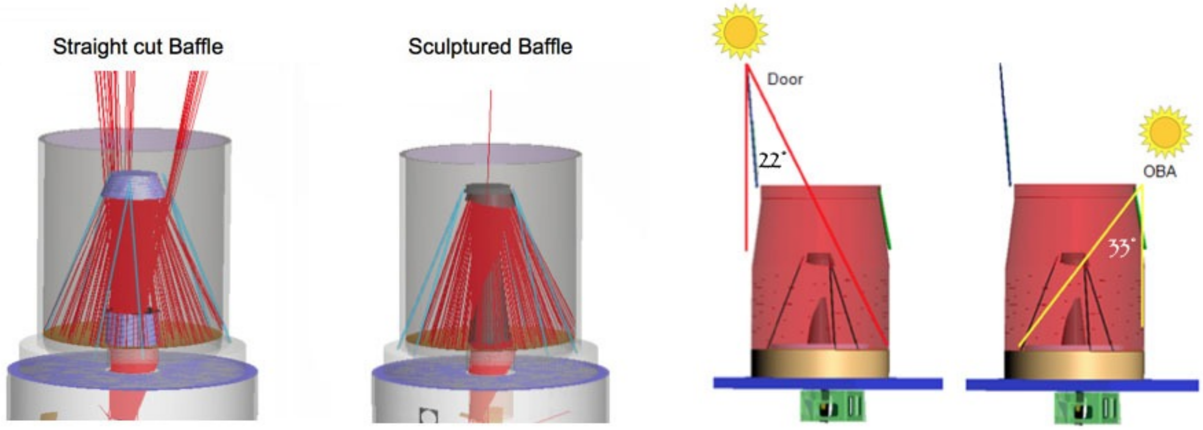

Figure 15. The Role of the Telescope Baffles in Controlling Rogue (Direct, out-of-field) Rays and Exclusion Angles.

The reverse ray trace (stray light model by Len Seals) with scatter allows the calculation of the Point Source Transmission (PST) curve for the system. The current analysis indicates that as long as there is not direct illumination on the primary mirror from the sun, earth or moon, the stray light requirement (<10% Zodiacal light background) is met. For the door side (sun side), this exclusion angle is >22° and the OBA in general is >33°.

10. Summary and Current Efforts

We have briefly described the WFIRST-AFTA concept study Wide Field Instrument's optical design. We have discussed design drivers, the functions of various features and modes, and systemic requirements and performance.

We are currently creating a full integration and testing flow plan, and associated bottom-up error allocation for predicted performance, including fabrication, I&T, cooldown and gravity release analysis. Joe Howard's JWST work on Linear Optical Models and MatLab CodeV extensions is being applied.[7,8] We are planning an expansion of IFU to include a second field (adjacent to current field) with a coarser sampling of 0.3'. Future design cycles will continue to explore options based on lessons already learned in current analysis.

It is significant to note that WFIRST-AFTA in the pre-phase-A stage of NASA missions. The WFIRST-AFTA study office at Goddard Space Flight Center continues to move the design options forward towards a robust design with reduction of risks. The goal is to be ready for a 2022–2024 launch date.

11. Acknowledgements

We sincerely acknowledge that this study is the product of a well-coordinated team. This includes the WFIRST-AFTA SDT (and the April 30, 2014 Interim Report), team co-members of many disciplines, contractors, and project leadership and support staff. This work was funded by the National Aeronautics and Space Administration (NASA.)

[1] Please refer to the WFIRST Project Page.: http://wfirst.gsfc.nasa.gov

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